Structure of ^{9}C from the $d(^{10}C,t)^{9}C$ Reaction and the Reliability of Ab-Initio Transfer Form Factors

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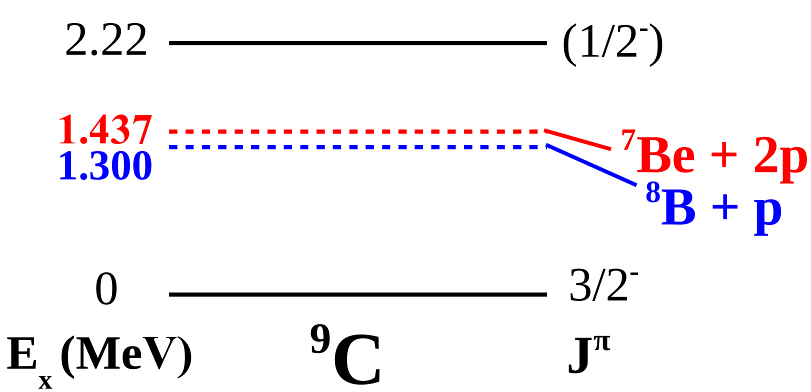
Western Michigan University

Nuclear Structure 2012
August 14th, 2012

Motivation: Nuclear Structure

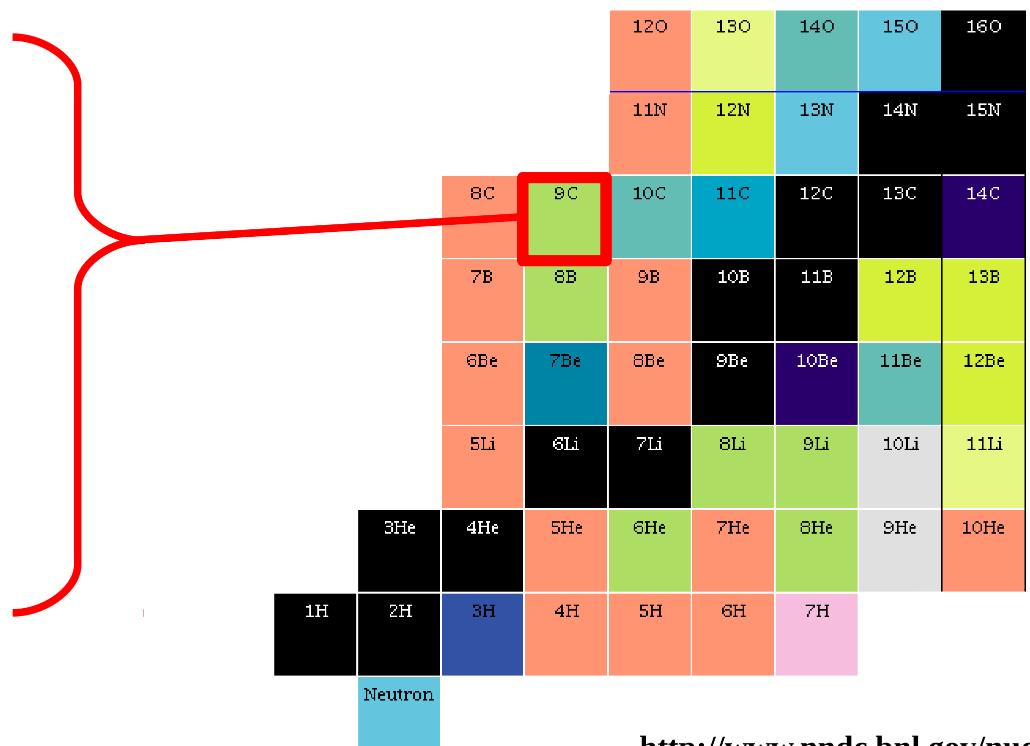
- Very little information exists for the neutron-deficient nucleus ^{9}C
- Mostly studied through complex multi-nucleon transfer reactions
- A few-nucleon system that *should* be well described by a naïve shell model
- ^{9}C ground-state magnetic dipole moment anomalously small compared to theory



$t_{1/2}$ = 126.5 ms

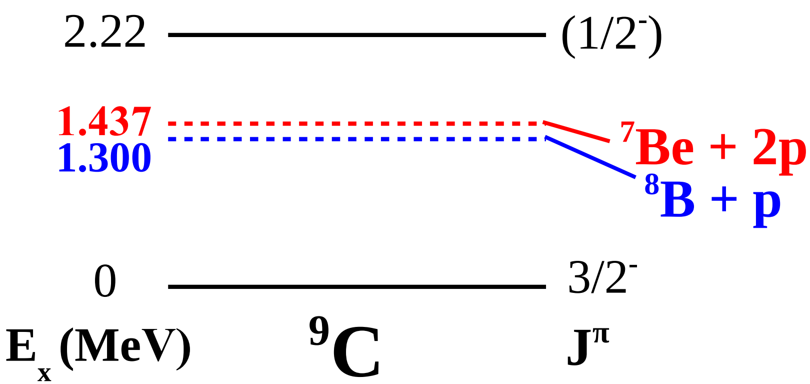
μ_{exp} = -1.3914 ± 0.0005 μ_N

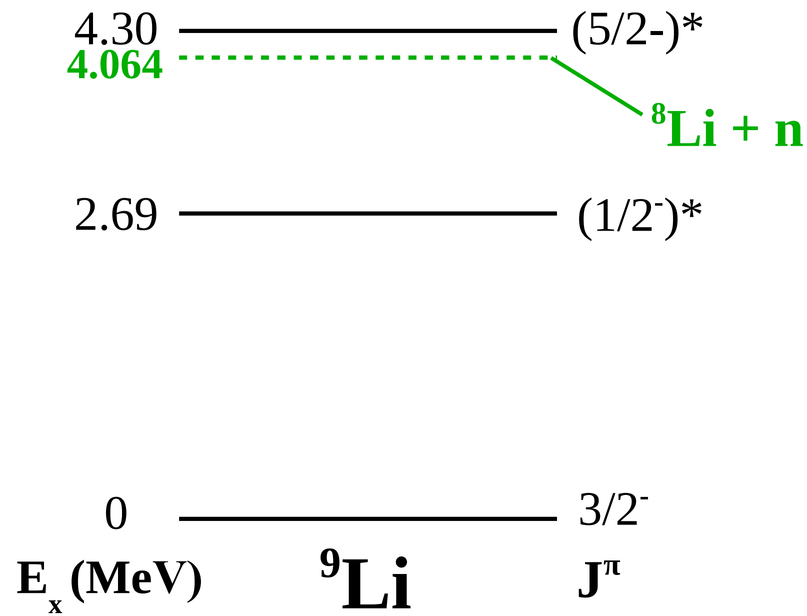
$\mu_{Schmidt}$ = -1.91 μ_N



http://www.nndc.bnl.gov/nudat2/

^{9}C Magnetic Moment Anomaly





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$\mu_{exp} = -1.3914 \pm 0.0005\ \mu_N$
$\mu_{Schmidt} = -1.91\ \mu_N$

$t_{1/2}$ = 178.3 ms

$\mu_{exp} = +3.4391 \pm 0.0006\ \mu_N$
$\mu_{Schmidt} = +3.79\ \mu_N$

- Difficult to develop a model which consistently calculates μ for both A=9, T=3/2 mirrors
- Possibility of higher-order configurations in the ^{9}C ground-state wave function
- Require more information on the single-particle structure of ^{9}C (and ^{9}Li)

***A. Wuosmaa et. al, Phys. Rev. Lett. 94, 082502 (2005).**

Motivation: Nuclear Theory

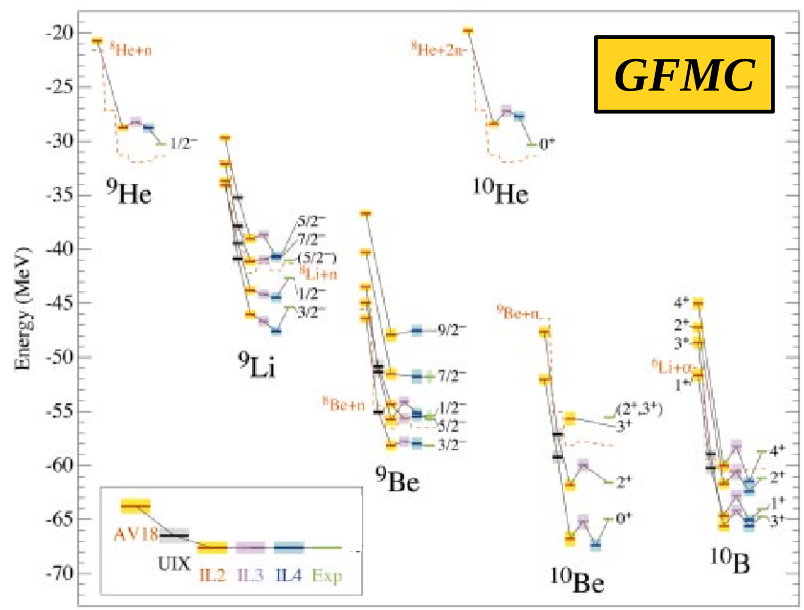
- In the past two decades, the refinement of *ab-initio* nuclear models which well reproduce observables for many light nuclei

- Various first-principle approaches have calculated energy levels, electromagnetic moments, charge and matter radii

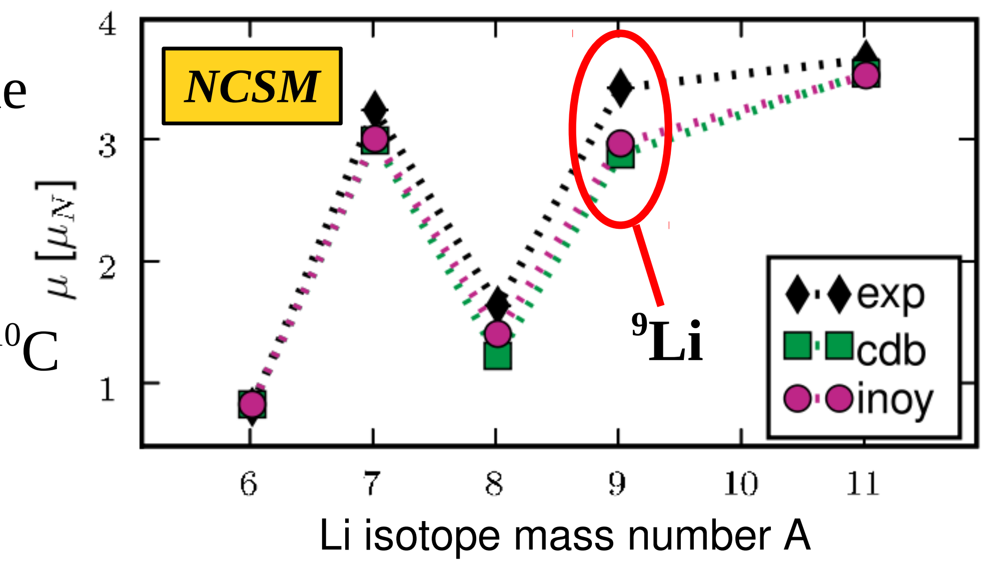
- Impetus to study unstable light nuclear systems in the *p*-shell to stringently test these models

- ^{9}C is a prime candidate being a drip-line nucleus and within the range of most *ab-inito* models

- Additionally, wave functions exist for ^{10}C which allows for the computation of the single-neutron densities and produce *ab-initio* spectroscopic factors



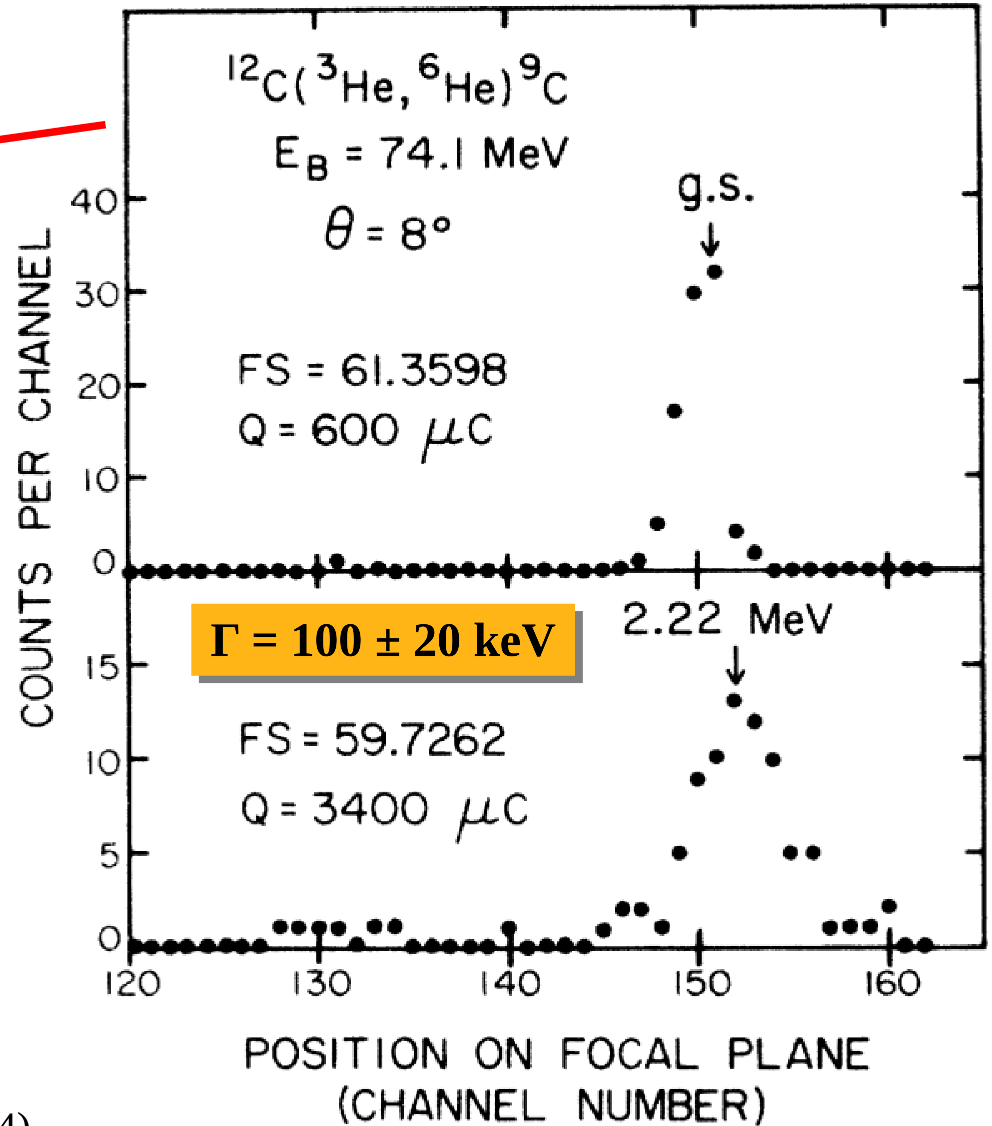
S. Pieper et. al, Phys. Rev. C 66, 044310 (2002)



C. Forssén, et. al, Phys. Rev. C 79, 021303(R) (2009)

Previous Studies of ^{9}C

- $^{12}C(^{3}He,^{6}He)^{9}C$
  - <u>1964</u>: **Discovery of the isotope [1]**
  - **First-excited state observed [2]**
- $d(^{8}B,n)^{9}C$ [3]
  - **First single-nucleon transfer to ^{9}C**
  - **Extracted ANC and calculated S_{18}**
- $p(^{8}B,^{8}B)p'$ [4]
  - **Probed *p*-unbound excited states**
  - ***R*-matrix analysis**
  - **Supports $J^{\pi}=1/2^{-}$ for first-excited state**
  - **Possible $5/2^{-}$ state at $E_x \approx 3.5$ MeV**



[1] J. Cerny, *et al.*, PRL **13**, 726–728 (1964).
[2] W. Benenson and E. Kashy, PRC **10**, 2633–2635 (1974).
[3] D. Beaumel, *et al.*, PRC **514** 226–232 (2001).
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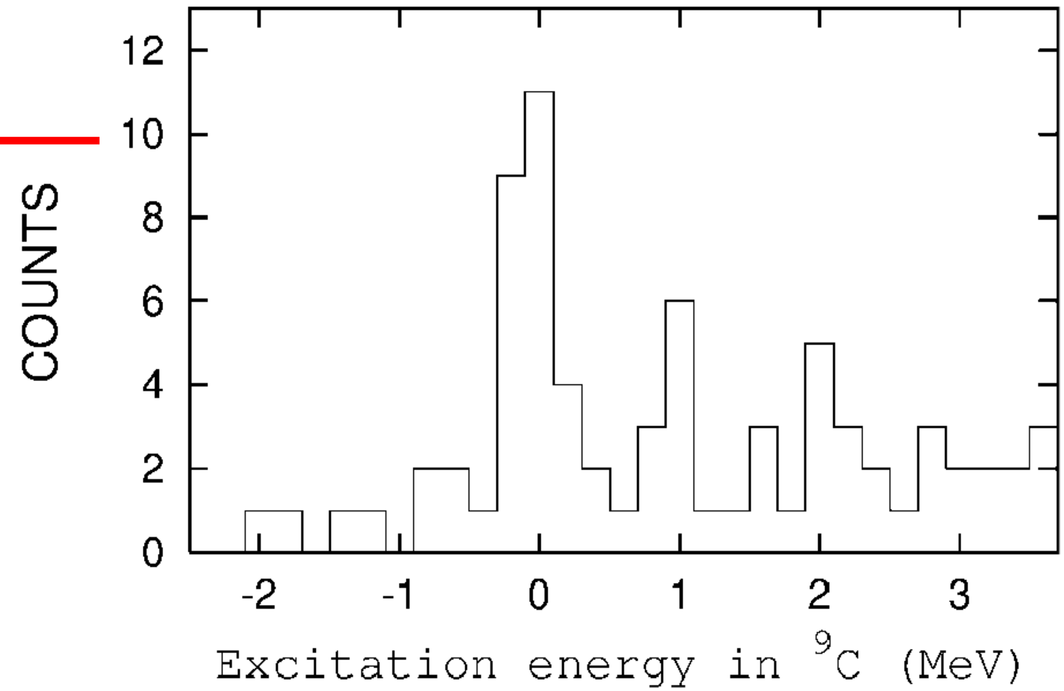

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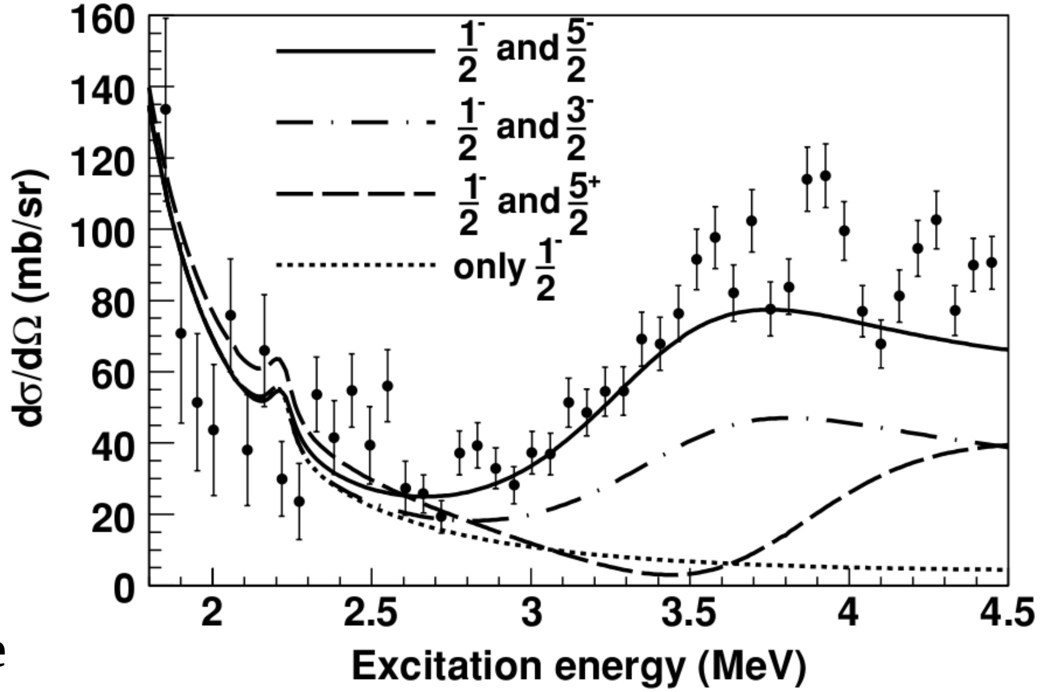

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^{9}C and Ab Initio Theories

PRL **106,** 162502 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

Knockout Reactions from *p*-Shell Nuclei: Tests of *Ab Initio* Structure Models

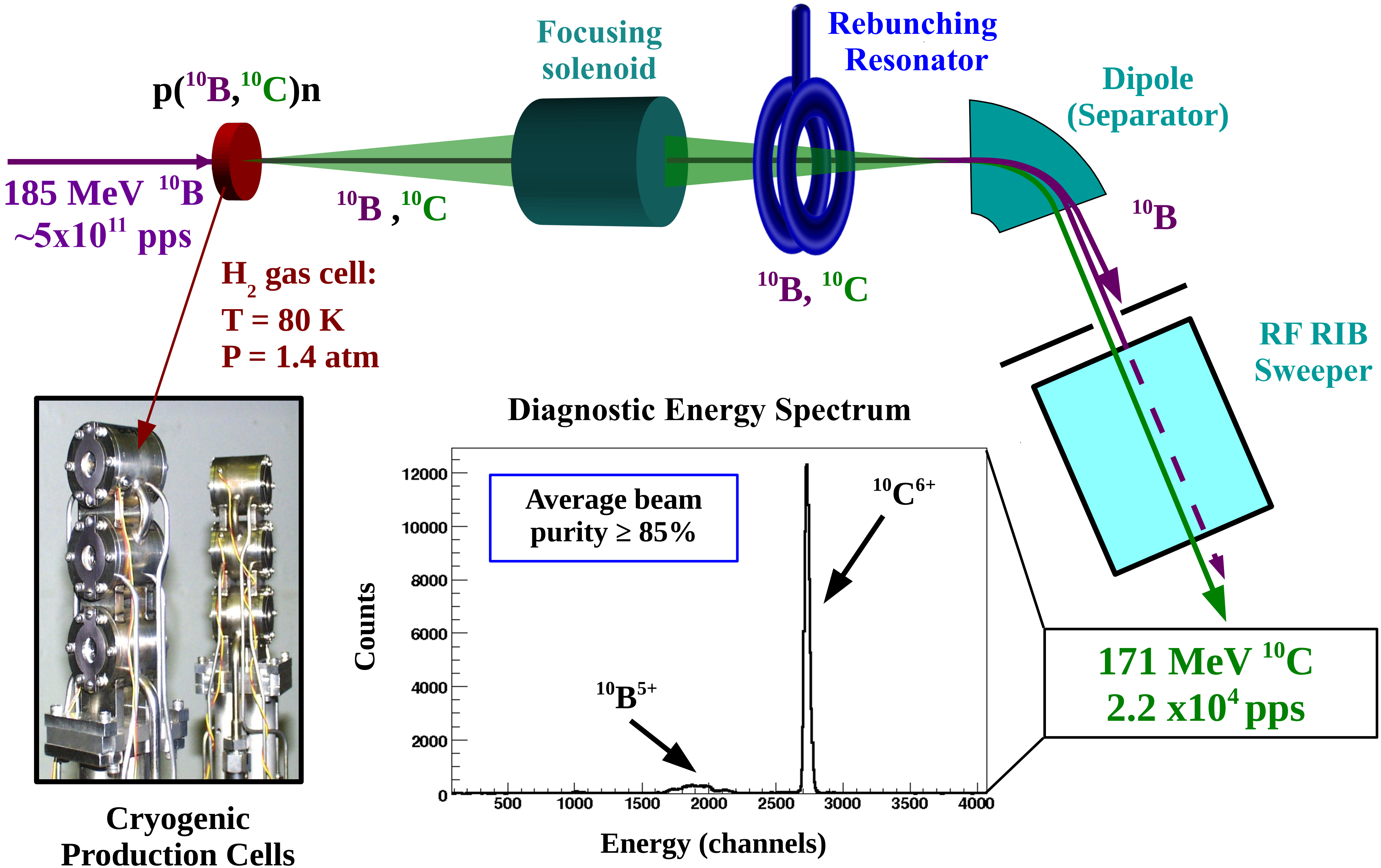
G. F. Grinyer,[1,*] D. Bazin,[1] A. Gade,[1,2] J. A. Tostevin,[3] P. Adrich,[1] M. D. Bowen,[1,2] B. A. Brown,[1,2] C. M. Campbell,[1,2] J. M. Cook,[1,2] T. Glasmacher,[1,2] S. McDaniel,[1,2] P. Navrátil,[4,†] A. Obertelli,[1,‡] S. Quaglioni,[4] K. Siwek,[1,2] J. R. Terry,[1,2] D. Weisshaar,[1] and R. B. Wiringa[5]

- **One-neutron knockout study at NSCL**
  - **Measured absolute cross section for ^{10}C → ^{9}C$_{gs}$+*n* and calculated neutron overlap**
  - **Compared to VMC and NCSM *ab initio* calculations ($\sigma_{exp} < \sigma_{ab\ inito}$, *30-50%*)**

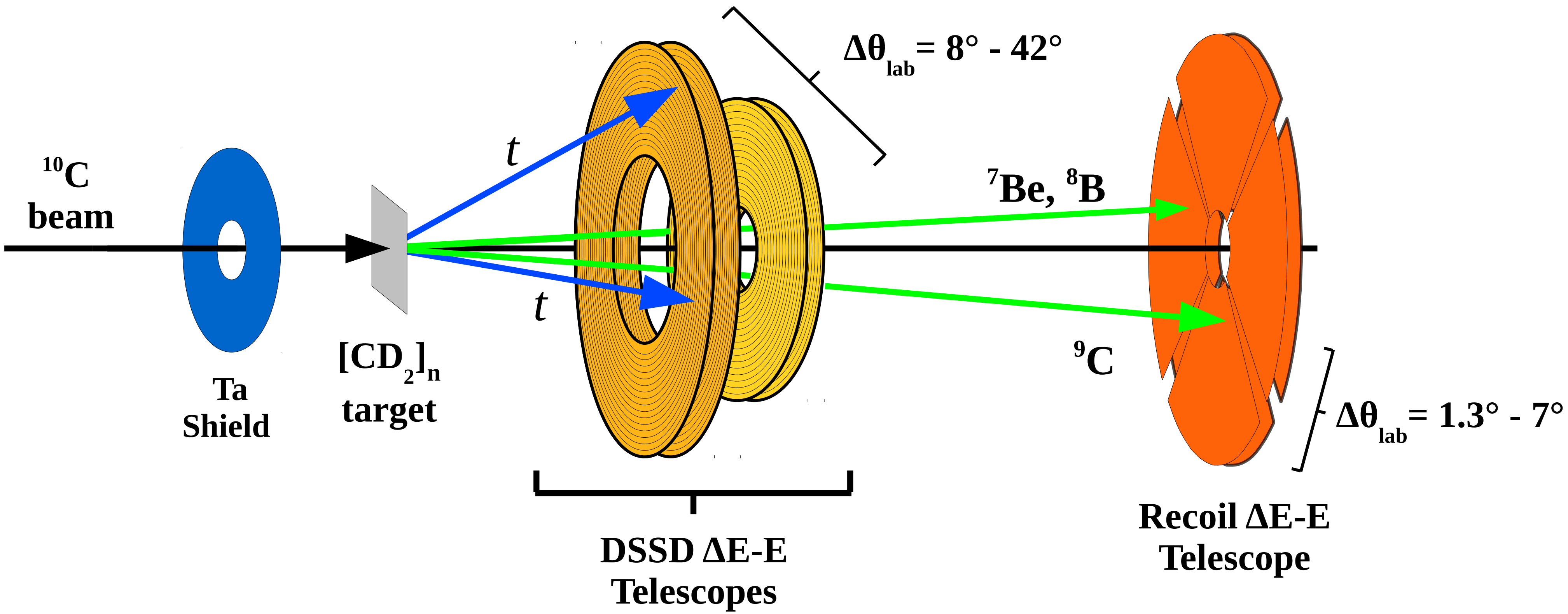
<u>Current Study</u>: *Populate ^{9}C using single-neutron transfer reaction*

- **Determine excited state energies, spin-parities, & extract spectroscopic information**
- **Compare to nuclear theories (including *ab-initio* calculations)**
- **Reaction will be in inverse kinematics and require a radioactive ^{10}C beam**
- **Selected reaction: $d(^{10}\mathrm{C},t)^{9}\mathrm{C}$ ($Q \approx -15$ MeV)**

^{10}C In-Flight Production at ATLAS



$d(^{10}C,t)^{9}C$ Experimental Setup



– Detectors were protected by 2 mm-thick tantalum collimator (10 mm aperature)

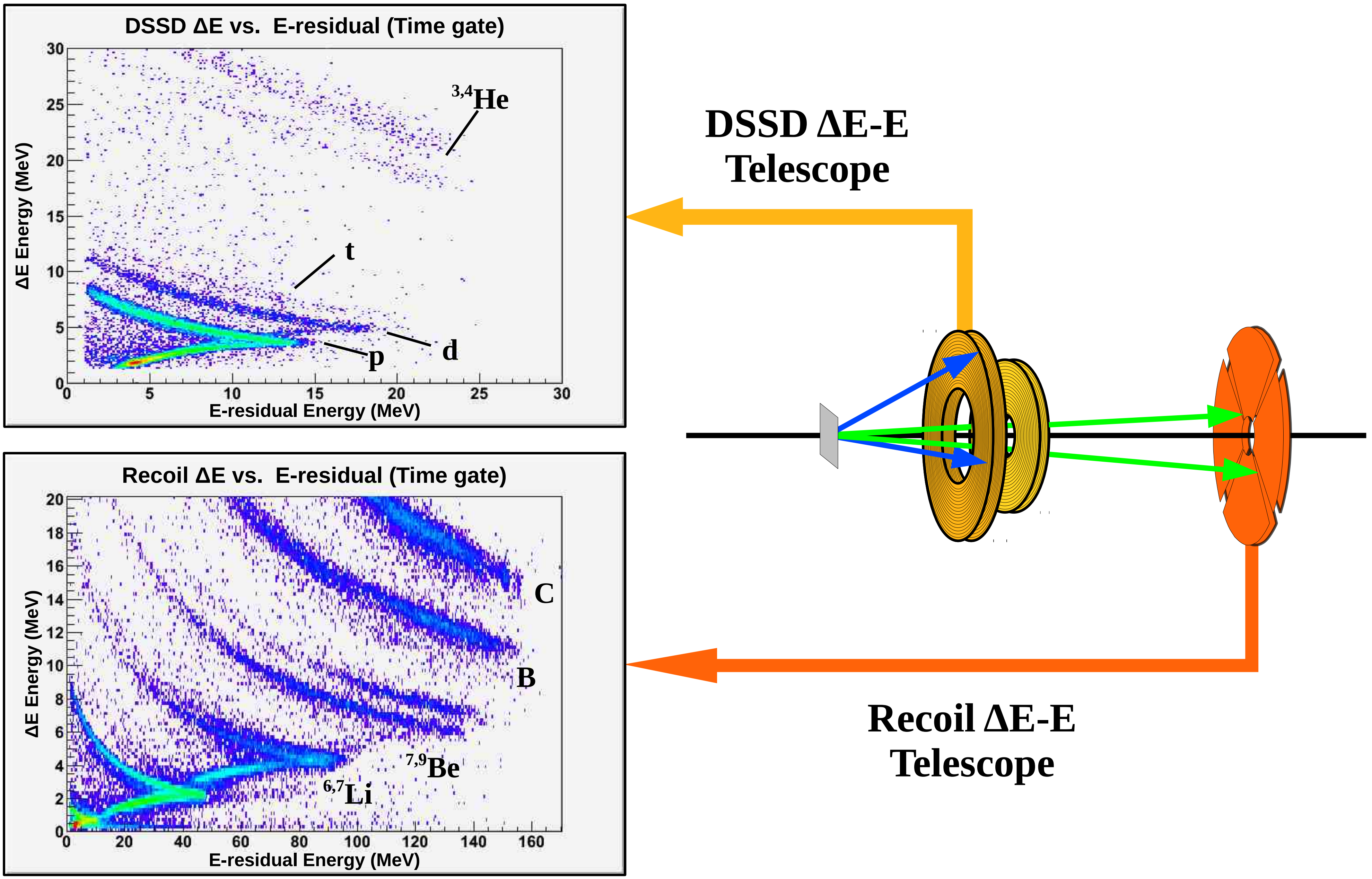
– Targets: 650 $\mu g/cm^2$ $[CD_2]_n$ and a 1.2 mg/cm^2 carbon

– Tritons were detected in two ΔE-E telescopes comprised of four annular DSSDs

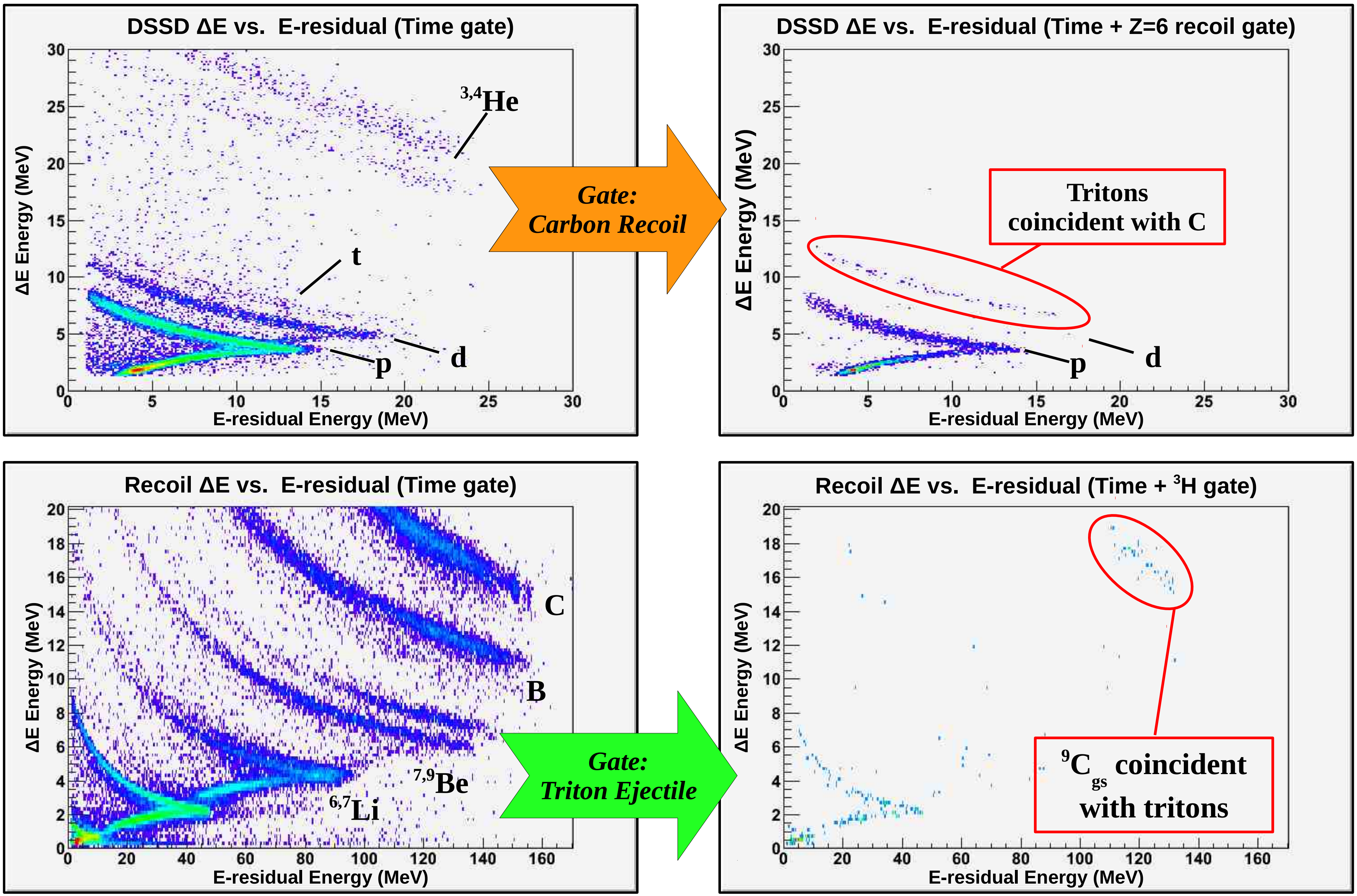
– Heavy, beam-like nuclei were detected in a four quadrant silicon ΔE-E telescopes

– Total radioactive beam time: ~6.5 days

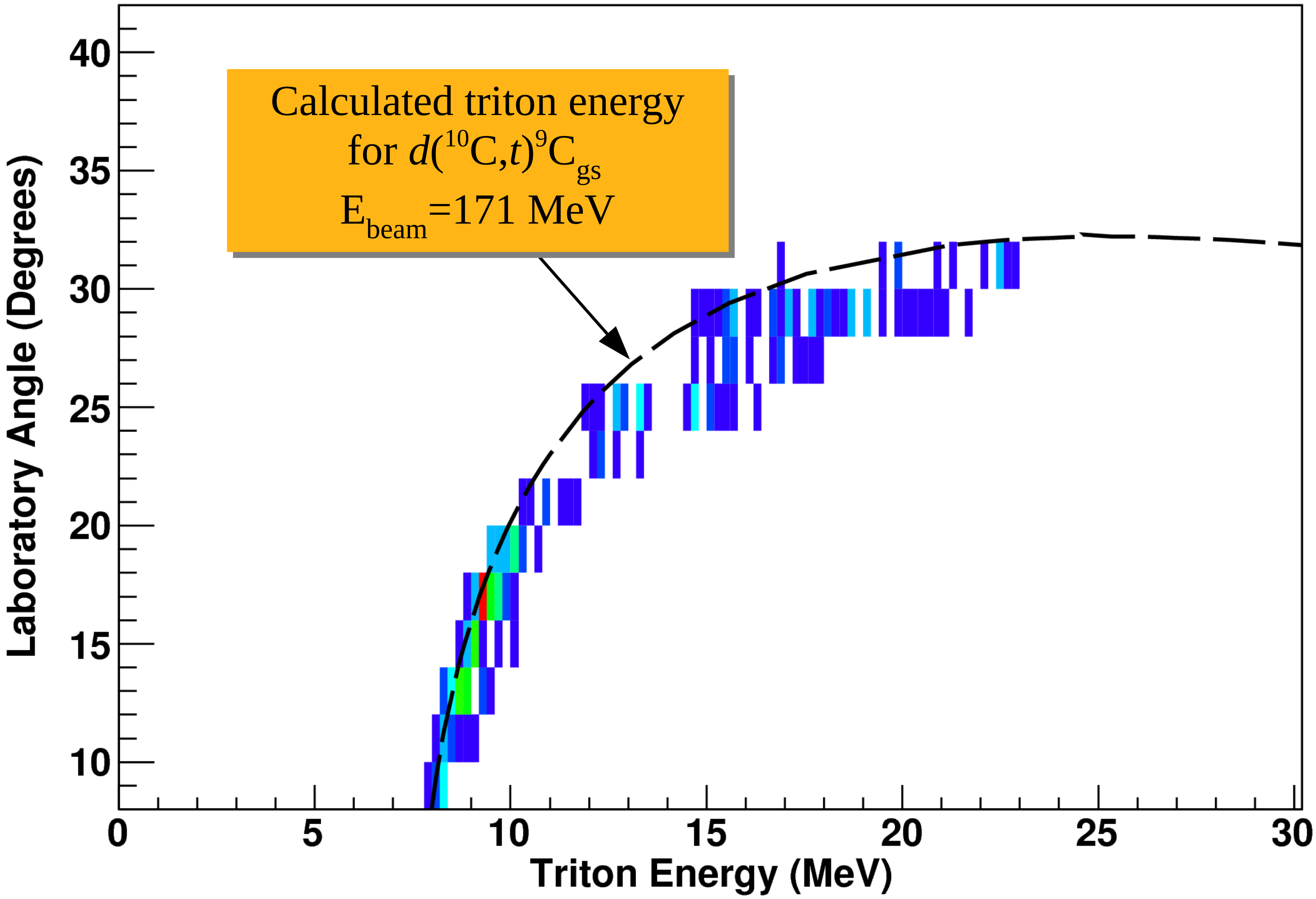
Particle Identification



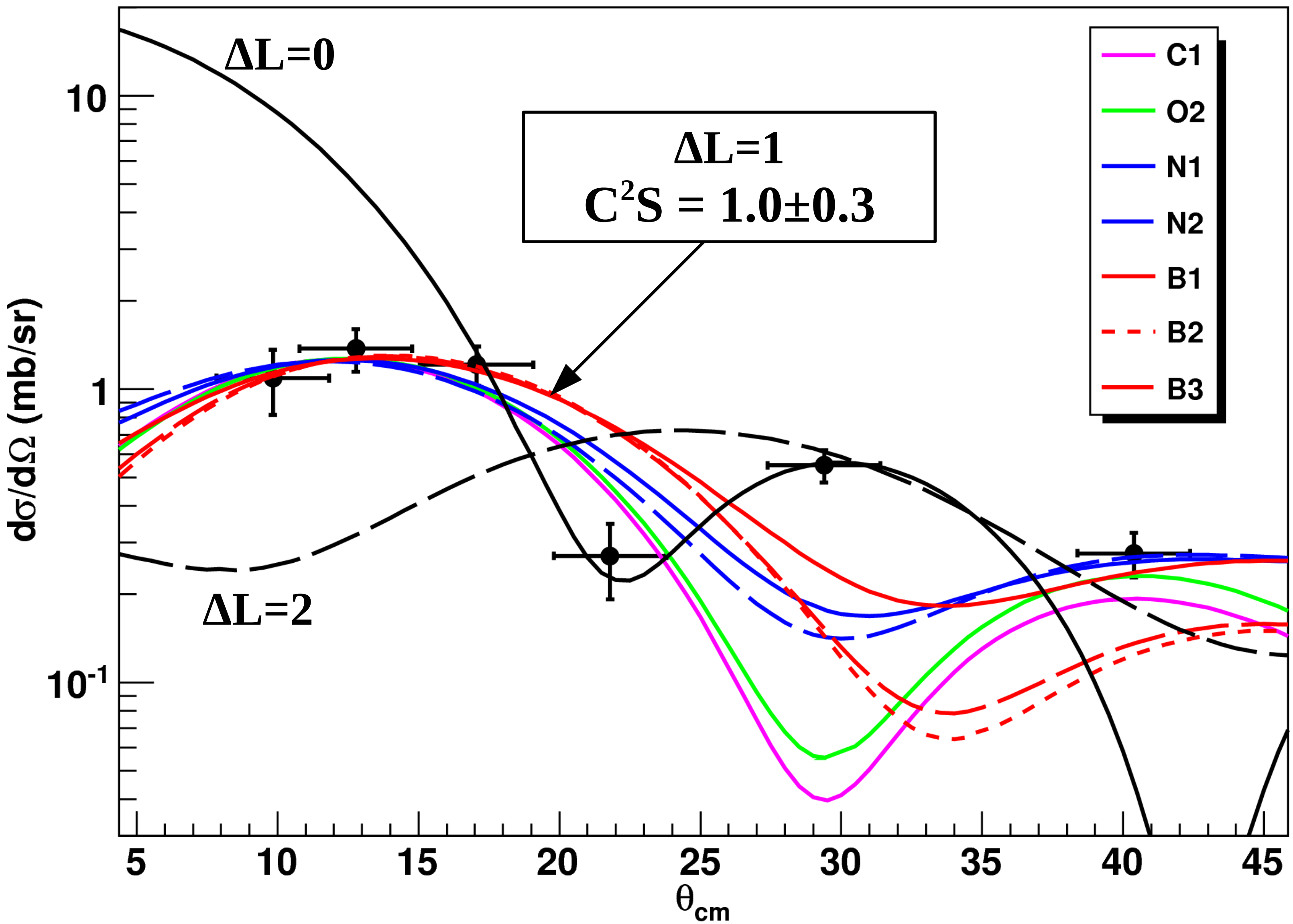
$d(^{10}C,t)^{9}C_{gs}$ Particle Gates



^{9}C Ground State – Triton Spectrum



Angular Distribution – $d(^{10}C,t)^{9}C_{gs}$



[C1,O1]: J.D. Cossairt, *et al.*, PRC **18**, 1 (1978).

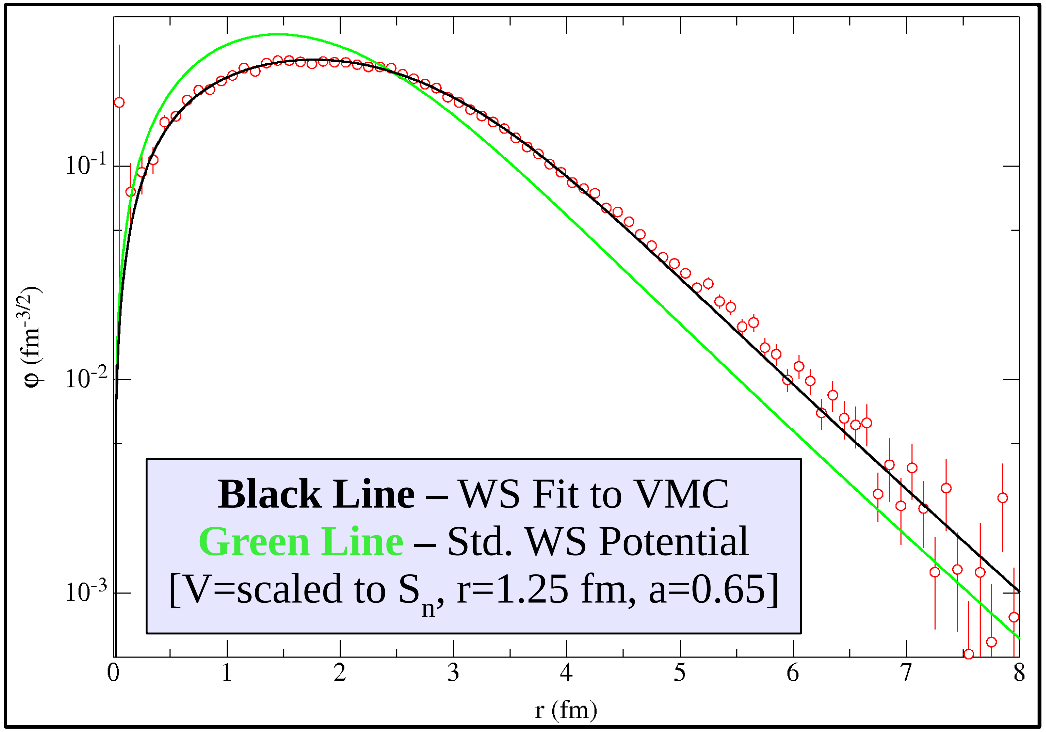
[N1-2]: F. Hinterberger, *et al.*, NP A**106**, 161−176 (1968).

[B1-3] C.M.Perey and F.G. Perey, Atomic Data and Nuclear Tables **17**,1 (1976).

VMC Transfer Form Factor: $d(^{10}C,t)^{9}C_{gs}$

- ***Test of the Variational Monte Carlo***
  - Use VMC structure information in DWBA calculations of the $d(^{10}C,t)^{9}C_{gs}$ transfer cross section
- ***Bound State Potentials***
  - Fit the VMC one-neutron overlap functions for both ^{10}C–$^{9}C+n$ and ^{3}H–$^{2}H+n$ systems with Woods-Saxon potentials
  - Use as bound-state potentials in DWBA calculations

(Red Points) VMC Single-Neutron Density: ^{10}C by ^{9}C(3/2^{-})+n



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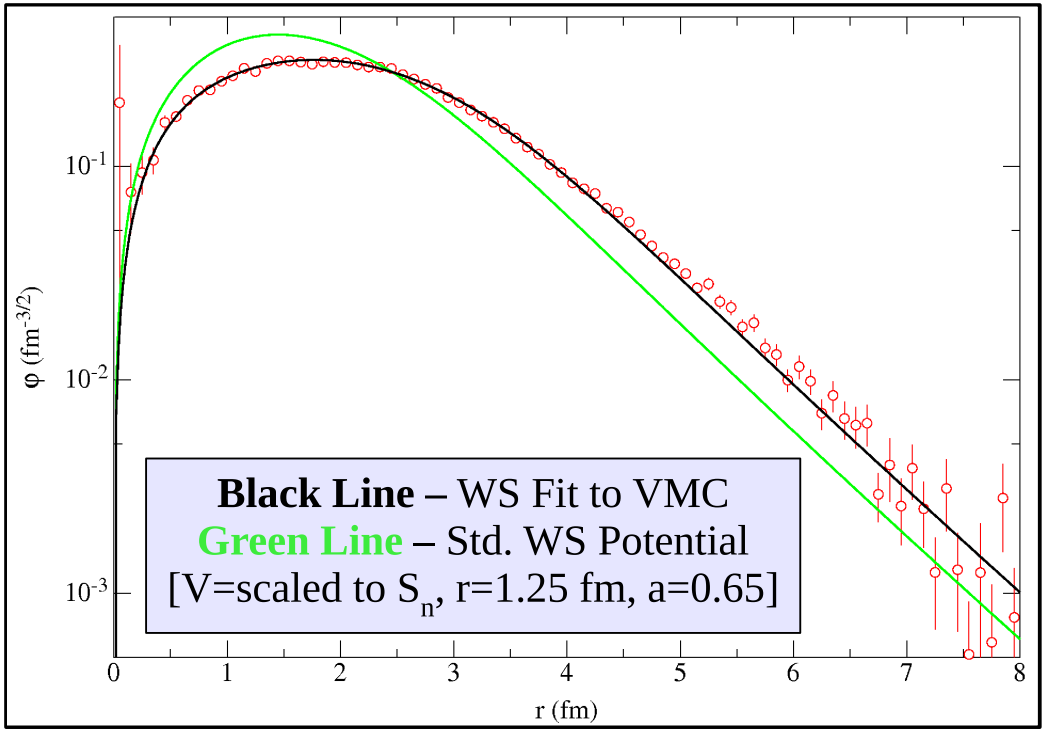


$$C^2S_{std}/C^2S_{VMC} = 3.4\pm0.3$$

The VMC-derived form factor yields cross sections ***larger*** than experiment

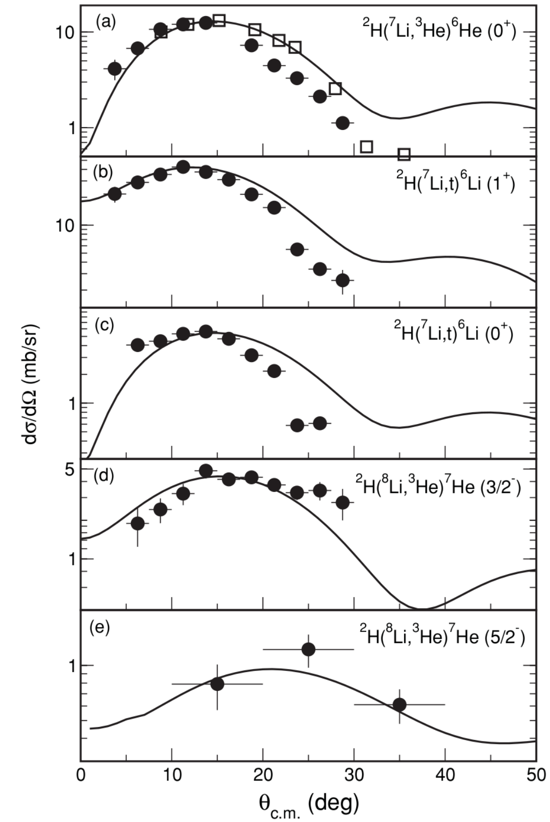
Consistent for all sets of incoming and outgoing optical-model parameters

VMC and *p*-shell Transfer Cross Sections

• "Enhancement" from VMC-derived form factors have been observed before in a previous *p*-shell transfer study:

$d(^{8}\mathrm{Li},{}^{3}\mathrm{He})^{7}\mathrm{He}$
$d(^{7}\mathrm{Li},t)^{6}\mathrm{Li}$
$d(^{7}\mathrm{Li},{}^{3}\mathrm{He})^{6}\mathrm{He}$

Produces cross sections x3 larger than experiment

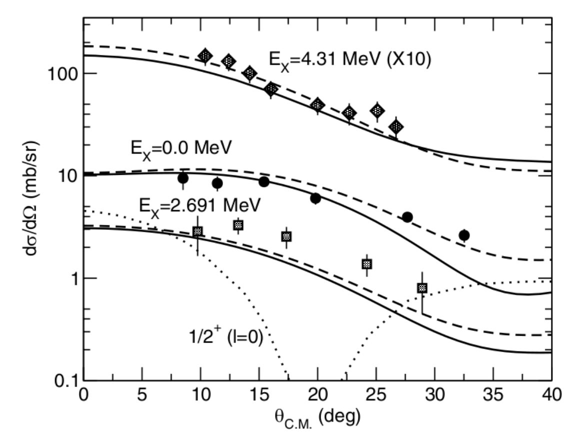


A.H. Wuosmaa, *et al.*, PRC **78**, 041302(R) (2008).

• However, the use of VMC form factor well reproduces (*d*,*p*) cross sections:

$d(^{8}\mathrm{Li},p)^{9}\mathrm{Li}$
$d(^{7}\mathrm{Li},p)^{8}\mathrm{Li}$
$d(^{6}\mathrm{Li},p)^{7}\mathrm{Li}$
$d(^{6}\mathrm{He},p)^{7}\mathrm{He}$

Within 30% of experimental values



A.H. Wuosmaa, *et al.*, PRL **94**, 082502 (2005).

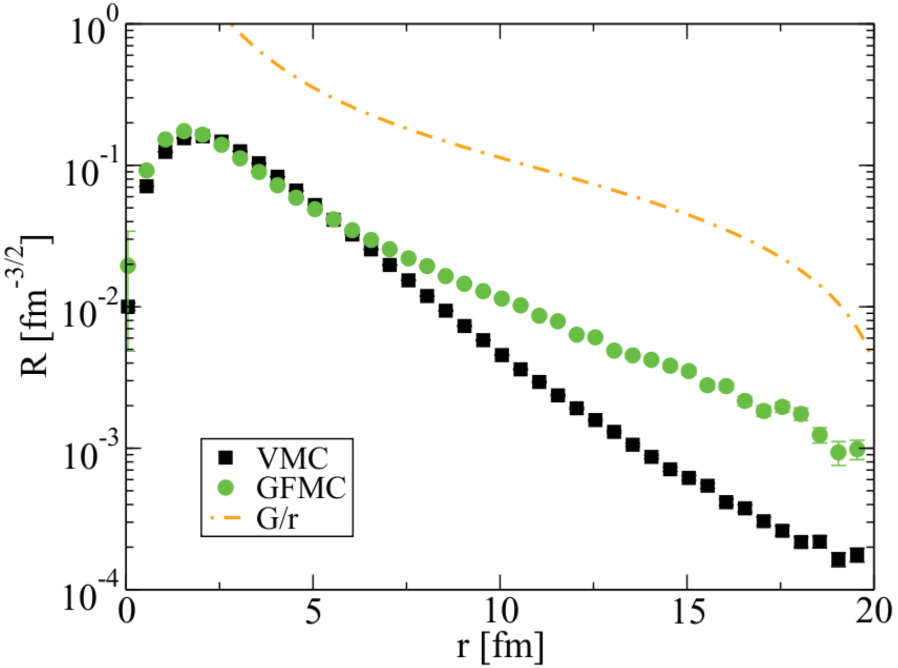
Implies a sensitivity of the DWBA reaction-theory calculations to VMC-derived form factors

Reaction or Structure Theory?

Possible sources of enhanced (*d*,A=3) cross sections produced by VMC-derived form factors...

- **Nuclear Theory:**
  - Asymptotic behavior of the VMC overlap functions
  - Green's function Monte Carlo (GFMC) calculations improve upon VMC overlaps at larger radii
- **Reaction Theory:**
  - No enhancement observed for p-shell (*d*,*p*) reactions...
  - Triton or ^{3}He ("outgoing") distorted waves
- **A combination of both?**

One-neutron overlap function for ^{7}He by ^{6}He+*n* from **VMC** and **GFMC** calculations



I. Brida, *et al.*, PRC **84**, 024319 (2011).

Further investigation is underway

Summary

- Successfully populated states in ^{9}C using the neutron-removing reaction $d(^{10}C,t)^{9}C$ with a radioactive ^{10}C beam
- Ground-state absolute spectroscopic factor determined with standard and VMC-derived form factors ($C^2S_{std} = 1.0 \pm 0.3$)
  - VMC-derived form factor produce larger cross sections relative to the standard form factor ($C^2S_{std}/C^2S_{VMC} = 3.4 \pm 0.3$)
  - Possible reaction-model and/or sensitivity to VMC inputs for $d(^{10}C,t)^{9}C$ as well as other *(d,t)* and $(d,{}^{3}He)$ reactions
- Further investigation of the enhancement of DWBA cross sections from form factors derived from VMC calculations is underway
  - Comparison to form factors from additional *ab initio* calculations (GFMC, NCSM, etc.)
  - Evaluation of reaction model calculations

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M. Alcorta, P.F. Bertone, J.A. Clark, C.M. Deibel[†], C.L. Jiang,

T. Palchan-Hazan, K.E. Rehm, A.M. Rogers, C. Ugalde[‡]

[†]LSU [‡]University of Chicago/JINA

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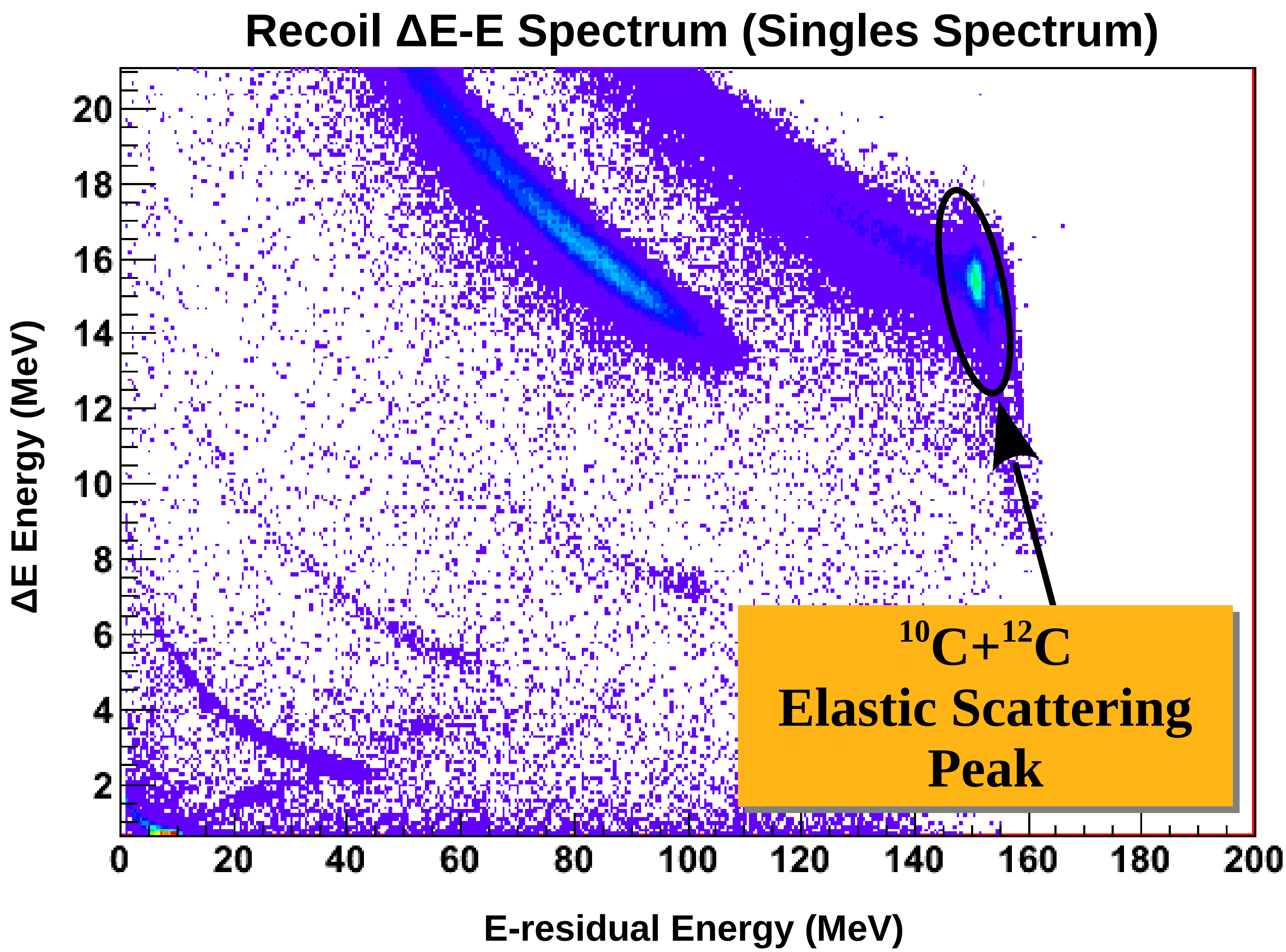
Grant numbers DE-FG02-04ER41320 & DE-AC02-06CH11357

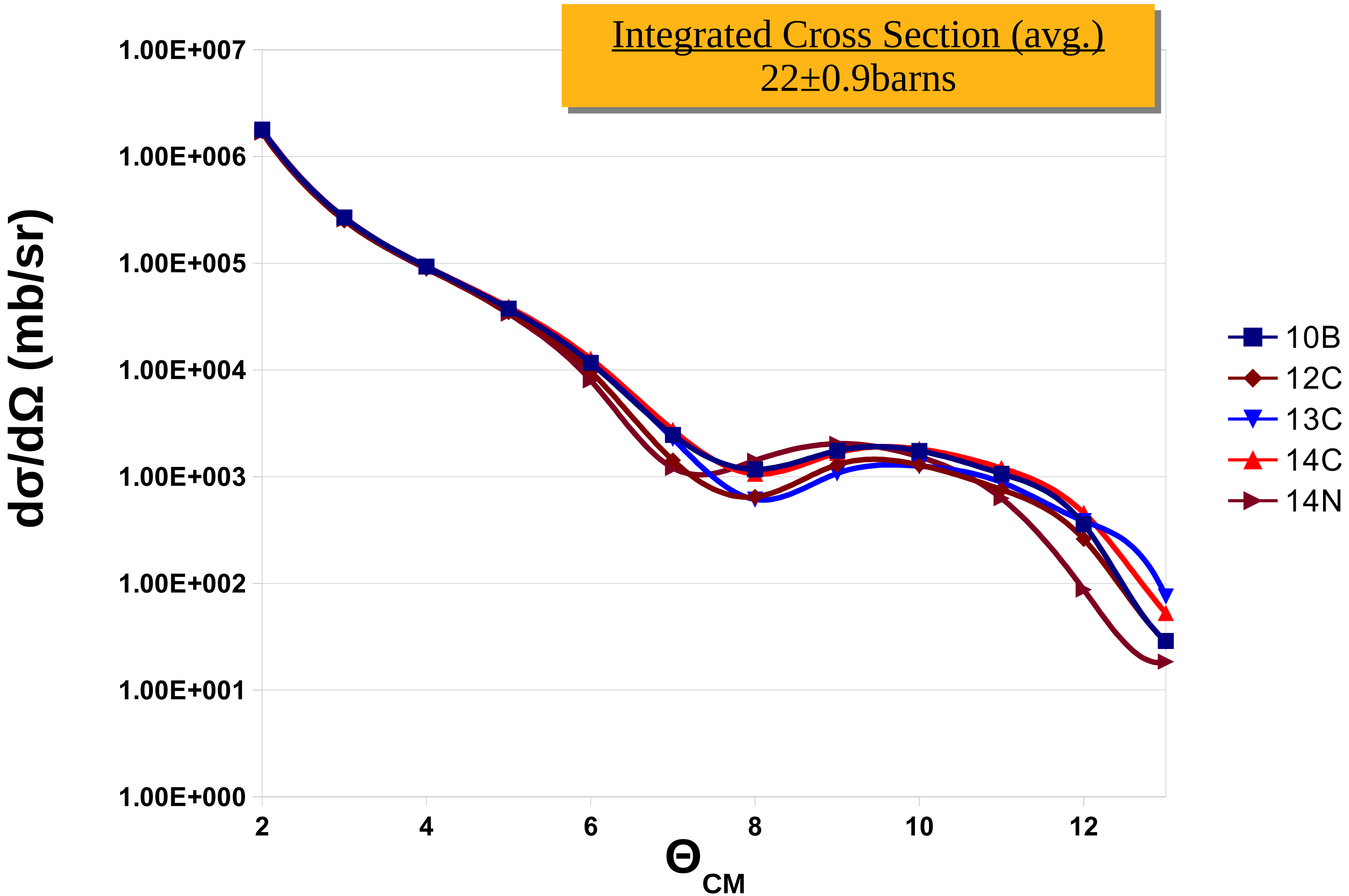
Beam Normalization



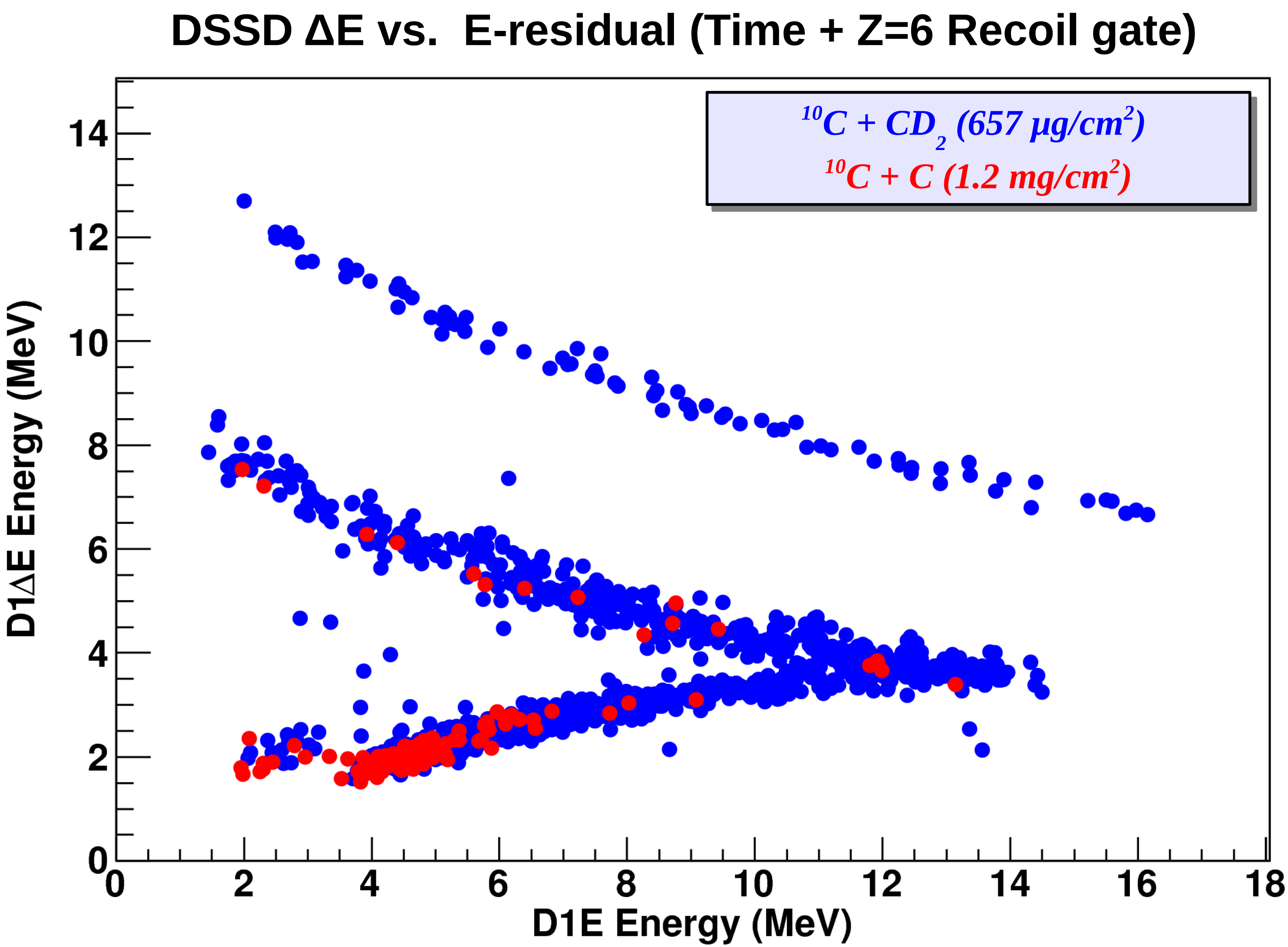
- Calculated $^{10}C+^{12}C$ elastic scattering cross section using PTOLEMY code
- Used ^{10}B, $^{12,13,14}C$, $^{14}N + ^{12}C$ elastic scattering potentials for $^{10}C+^{12}C$ system

Beam Normalization

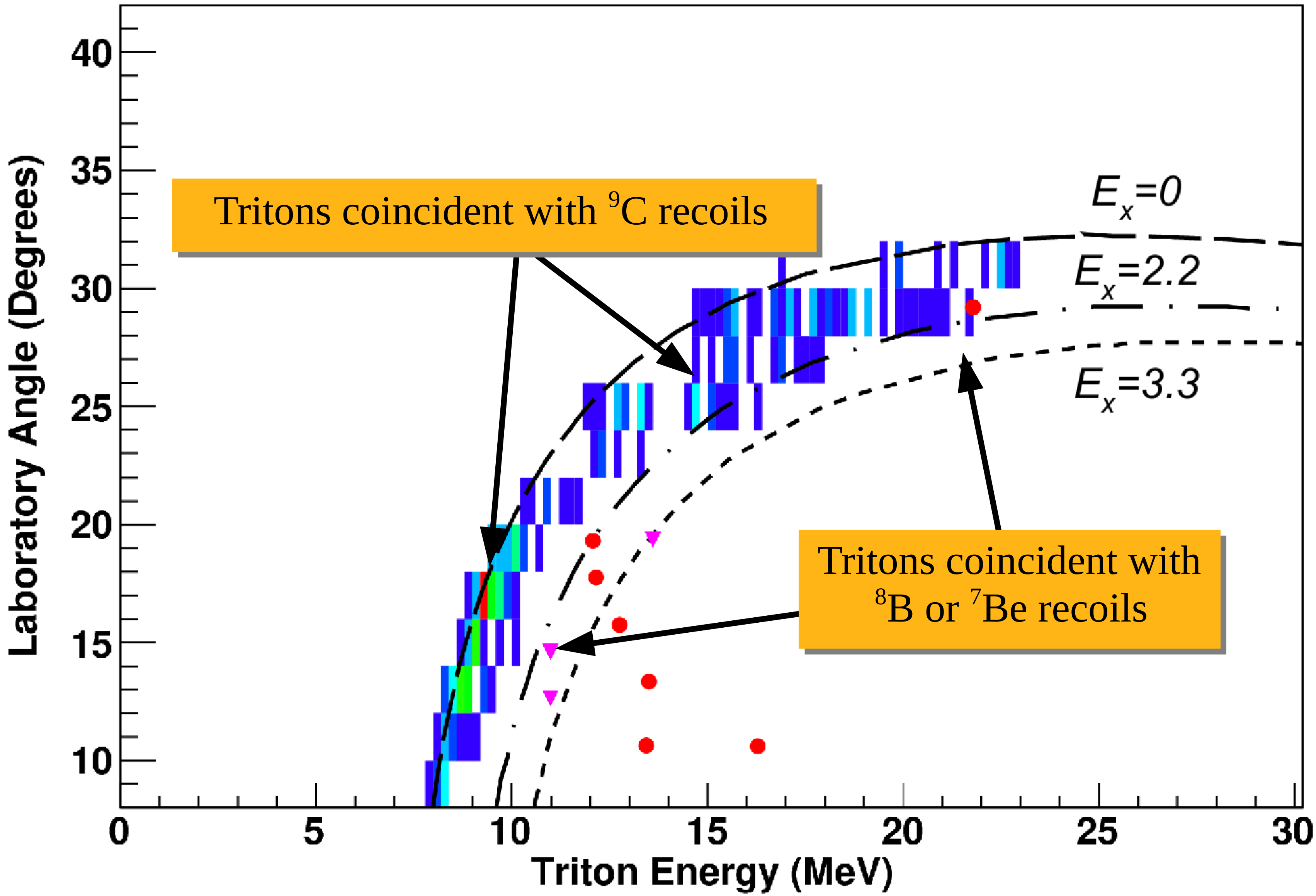
Angular Distribution $^{10}C+^{12}C$ elastic @ E_{CM}=93.2 MeV



Backgrounds



$d(^{10}C,t)^9C$ Triton Spectra



^{9}C Excitation Energy Spectrum